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The primary effort of this project has been to develop and evaluate passive sonar receiver structures that make use of knowledge of the environment and received signal characteristics to detect, localize and classify the passive source, particularly in shallow water. Several structures have been or are being investigated.
In shallow water, passive sonar context, the characteristics of received signals are determined by the properties of the source and by propagation through the ocean. Our hypothesis is that knowledge of the environment can be used to estimate propagation effects, which then provide information about the source location. Because the ocean environment is dynamic and variable in time and space, a statistical approach is necessary.

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Re: Final Technical Report, Award N0014-12-1-0222

The enclosed report is submitted as required under block 31 of the subject award.

Sincerely,

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# REVEAL:
# Receiver Exploiting Variability in Estimated Acoustic Levels

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## LONG-TERM GOALS

The long-term goal of the REVEAL project is to develop and demonstrate a passive sonar signal processing structure that exploits available knowledge of the environment, including uncertainty, to detect, localize and classify targets.

## OBJECTIVES

The FY12 objectives were to:

- Continue development and evaluation of a striation-based processor for passive sonar localization, and apply the algorithm to the south Florida array CALOPS data.
- Apply the mode space processor developed by Premus to estimate passive source depth using horizontal and vertical line arrays to data from the NURC REP11 B data, and evaluate sensitivity to key environmental factors.

## APPROACH

The primary effort of this project has been to develop and evaluate passive sonar receiver structures that make use of knowledge of the environment and received signal characteristics to detect, localize and classify the passive source, particularly in shallow water. Several structures have been or are being investigated.

In shallow water, passive sonar context, the characteristics of received signals are determined by the properties of the source and by propagation through the ocean. Our hypothesis is that knowledge of the environment can be used to estimate propagation effects, which then provide information about the source location. Because the ocean environment is dynamic and variable in time and space, a statistical approach is necessary.

## WORK COMPLETED

In a shallow water waveguide, where the distance between an acoustical point source and receiver is several times greater than the water depth, the resulting pressure field may be expressed by a finite sum of normal modes. A superposition of modes represents the sound pressure at the receiver, i.e.

$$P(r,z_r,z_s)=\sum_{n=1}^{N}B_n(z_r,z_s)\exp[ik_{rn}r] \quad , \tag{1}$$

when the depth of the source, $z_s$, and range, $r$, from the omnidirectional point receiver located at depth, $z_r$, are known and

$$B_n(z_r,z_s)\equiv\left(\frac{2\pi}{k_{rn}r}\right)^{1/2}\psi_n(z_r)\psi_n(z_s) \tag{2}$$

represents the contribution from each mode. The mode eigenfunctions and eigenvalues are, $\psi_n(z)$ and $k_{rn}$, respectively, and $k_{rn}$ is the horizontal component of the wavenumber for mode m. Lastly, the number of modes contributing to the pressure field $N$ is a function of source frequency and waveguide depth.

If the acoustical source frequency is high enough to excite more than one propagating mode in the waveguide, the modes will interact with one another to create an interference pattern in range, depth, and frequency. Writing the difference in mode wavenumbers as $\Delta k_{nm}(\omega)\equiv k_{rm}(\omega)-k_{rn}(\omega)$, where $m\neq n$, the received pressure spectrum can be written as

$$I(r,z_r,z_s,\omega)=|P|^2=\sum_m\sum_n B_mB_n^{*}\exp[i\Delta k_{nm}(\omega)r]. \tag{3}$$

Equation (3) describes the intensity interference pattern between different modes excited by a broadband noise source. This interference pattern can be seen as spectral striations, which have unique character determined by the relative location of the source and receiver in the waveguide, as well as the parameters that describe the waveguide.

Equation (3) also provides a method of determining the full intensity field based upon the waveguide parameters, however, it is useful to relate these parameters to lines of constant intensity within the full field. Setting the derivative of Eqn. (3) equal to zero, a constant intensity contour may be described as

$$dI(r,\omega)=\frac{\partial I}{\partial\omega}\Delta\omega+\frac{\partial I}{\partial r}\Delta r=0 \tag{4}$$

where $\Delta\omega=\omega-\omega_0$ and $\Delta r=r-r_0$. Using Eqns. (3) and (4), and solving for the slope of the contour in the range-frequency plane yields

$$\frac{\Delta\omega}{\Delta r}=-\frac{\omega_0}{r_0}\frac{\Delta k_{mn}(\omega)/\omega}{\partial\Delta k_{nm}(\omega)/\partial\omega}=-\frac{\omega_0}{r_0}\frac{\Delta S_p^{mn}(\omega)}{\Delta S_g^{mn}(\omega)}. \tag{5}$$

The contours are typically line-like and are often referred to as striations. In Eqn. (5), the mode-dependent wavenumber terms have been identified as group and phase slowness, $S_g$ and $S_p$. Using the

WKB approximation[4], it is possible to show that the relationship between $S_g$ and $S_p$ does not depend on either mode number or frequency. This leads to identification of the waveguide invariant, $\beta$, defined by Chuprov[1] as

$$\frac{\Delta\omega / \omega_0}{\Delta r / r_0} = -\frac{\partial S_p}{\partial S_g} \equiv \beta . \tag{6}$$

The waveguide invariant is a useful parameter for range estimation because it relates striation slope taken from observed interference patterns to $r_0$, the range between the source and receiver and $\omega_0$, the center frequency of the band in which the striation is observed. More detailed derivations of the waveguide invariant may be found in other references[1,2,5,6,7].

## RESULTS

The algorithm just described was applied to data from an experiment which took place along the continental shelf, east of Port of the Everglades, Florida. Acoustical data were taken using a 118 element horizontal line array (HLA) positioned on the sea floor in approximately 260 m of water. The HLA was approximately 220 m long and was oriented from west to east. In addition, the *R/V Seward Johnson* transited northward from the array with an acoustical source towed at a depth of 100 m. Although the towed source is not of interest in this paper, the *Seward Johnson*, recorded data using her radar's Automatic Identification System (AIS), which provided position data for surface vessels within 25 km of the HLA. The AIS ship position data were used as ground truth in the localization tests presented below.

Over the course of the experiment, numerous sound velocity profile (SVP) measurements were made from the *Seward Johnson* using stationary casts of a conductivity, temperature, and depth (CTD) sensor and moving casts with expendable bathythermographs (XBT). The sediment parameters used for modeling were taken from Greene et al.[3] Although sediment parameter data exist for this area, they are by no means complete and thus add uncertainty to the results presented in the next section.

In order to estimate range using spectral striations seen in range-frequency surfaces, Eqn. (6) must be solved for source range, $r_0$, to yield

$$r_0 = \omega_0 \left( \beta / S \right) \sin(\phi) \tag{6}$$

where the striation slope is $S = \Delta\omega / \Delta r$. The source is at angle $\phi$ from HLA broadside direction and is sufficiently far from the array such that received signals may be approximated as plane waves. The angle to the source may be determined using conventional beamforming. Spectral processing then is done for each channel in the HLA in order to obtain the range-frequency interference pattern along the array. Striation slope may be discerned from the spectrograms, as shown for example in Fig. (1). This method, however, is limited in cases where the source azimuth angle is close to broadside, otherwise the projected aperture may be insufficient to observe variations in frequency spectra along the array.

The remaining part of Eqn. (6) that must be estimated is the waveguide invariant, $\beta$. For cases where the shallow water environment is poorly known, and the source is known to be near the surface, a value of one can be used for $\beta^1$. However, this is a poor approximation for some scenarios because the SVP, receiver depth, and bathymetry between the source and receiver affect the value of the waveguide invariant. Any one of a number of Normal Mode methods[1,2,5,6,7] may be used to determine $\beta$ depending on the type of environment and the degree to which its features are known.

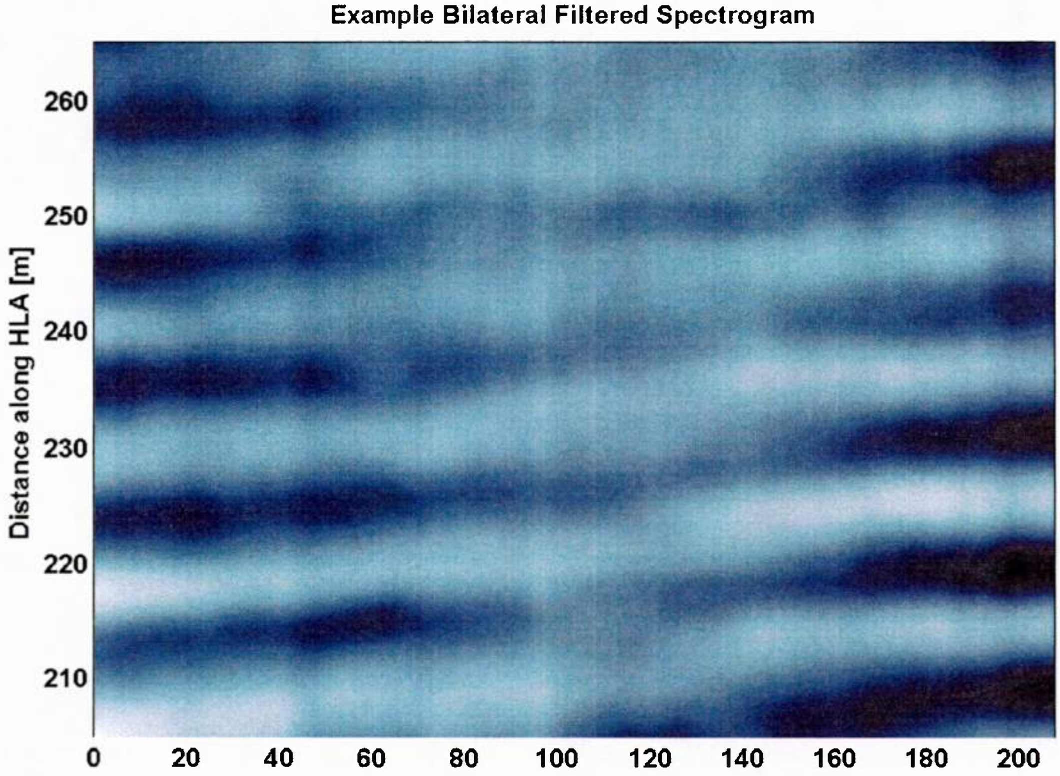


**Figure 1: Spectrogram showing striations in the receive intensity.**

During the eighth hour of acoustical "Run 1 North" in the CALOPS experiment, the cargo ship *Socol 2* passed just west of the HLA traveling northward. Her closest point of approach (CPA) to the array was approximately 2.5 km, and a sufficient amount of broadband, noise was radiated to excite the waveguide and create visible spectral striations along the array. Figure (1) shows the character of the interference patterns seen during this part of the dataset. These striations are quite clear, however, current effort is focussed on producting interference patterns which are clearly visible and useable for slope estimation.

In order to accurately resolve the striations, a number of image processing schemes were investigated. The spectrograms were first normalized at each frequency to remove completely horizontal features. They were then processed using a bilateral filter[8] to accentuate larger features (e.g. striations) and remove speckle. The result was spectrograms with far more apparent striations, when striations were present. Even with the aforementioned processing, the resulting spectrograms showed substantial fading over the length of the HLA. The final processing step was to average 10, 1 second snapshots to create the an image used for slope estimation.

Estimated striation slopes were used in Eqn. (6) to yield the range estimates shown in in Fig. (2). In addition to showing range estimates using $\beta = 1$, the Range Dependent Waveguide Invariant Distribution (RaDWID)[7] method was used to estimate $\beta$ based on known environmental parameters. Using RaDWID, estimated values for $\beta$ were closer to 0.8 and thus decreased the estimated range values. At close range the range estimates are within +/- 500 m of true range. However, as the source moves away from the HLA and the actual striation slope decreases, small errors in slope estimation result in larger range estimation errors. Also of note are the gaps present before minute 36, between minutes 42 and 46, and after minute 52. These were instances where striations were not apparent in the spectrograms.

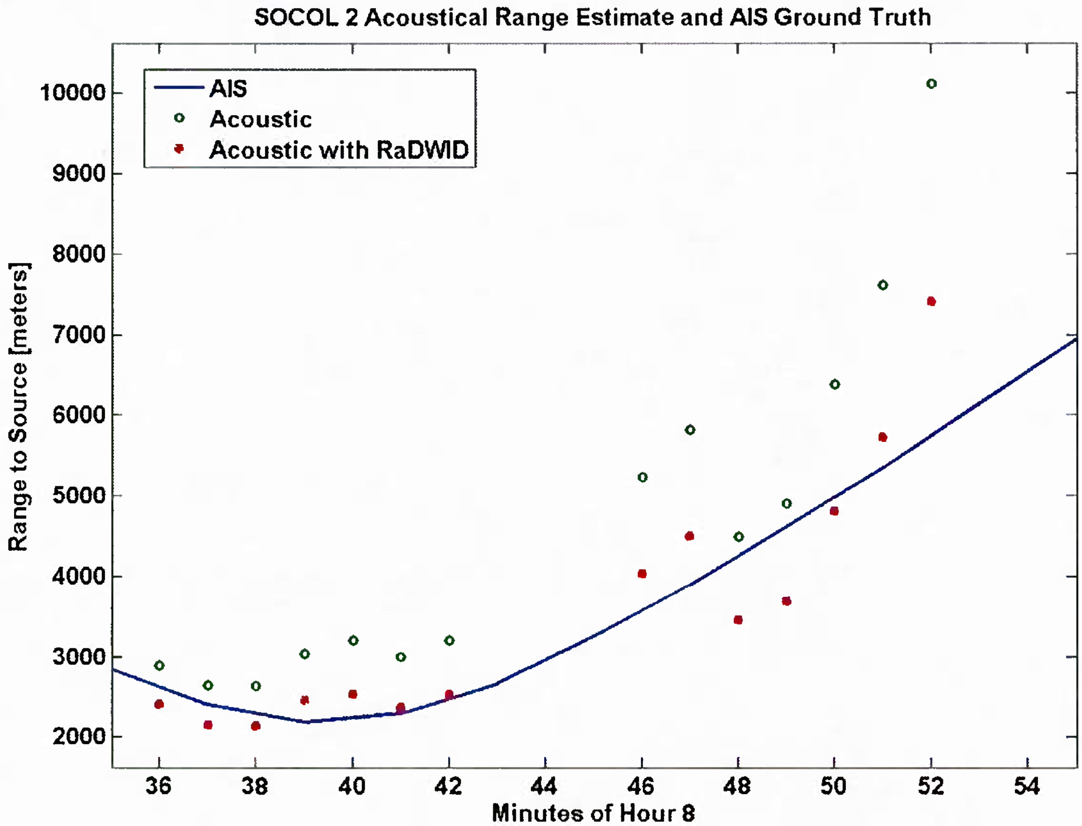


**Figure 2: Estimated source range (circles) and ground truth (line).**

We discuss two possible mechanisms which might explain the absense of visible striations during certain intervals. First, before minute 36, the ship aspect angle was just off of the bow and well forward of the beam. Thus the hull of the ship might block propulsion noise (i.e. from the propeller and machinery). Second, the range from the ship to the HLA was lower between minute 42 and 48,and it is possible that the direct path was much stronger than the multipath signal, resulting in only weak interference.

## IMPACT/APPLICATIONS

This research appears to offer a new automation capability for localizing passive sonar sources. The algorithms can be applied to any undersea sensor, such as a submarine hull or towed array or a fixed sensor mounted on the ocean floor.

## TRANSITIONS

The striation-based localization algorithm was been proposed for the FY 13 submarine Advanced Processing Build (APB 13) program but was not funded. The algorithm will be proposed again for APB15.

## RELATED PROJECTS

None.

## REFERENCES


1. S.D. Chuprov "Interference structure of a sound field in a layered ocean," in *Ocean Acoustics, Current State*, edited by L.M. Brekhovskikh and I.B. Andreevoi, Nauka, 71-91, (1982).
2. G.L D'Spain and W.A. Kuperman, "Application of waveguide invariants to analysis of spectrograms from shallow water environments that vary in range and azimuth," *J. Acoust. Soc. Am.* **106**(5), 2454-2468, (1999).
3. R.R. Greene, G.T. Hebenstreit, and B.J. Sperry, "Environmental Acoustic Modeling of the Acoustic Observatory Site and Implications for the Performance of Adaptive Beamformers," *IEEE*, **1**, 421-425, (2002).
4. V.A. Polyanskaya, "The field of a pulse radiator in an underwater sound channel," *Akutst. Z.* **5**, 91-100, (1959).
5. D. Rouseff and R.C. Spindel, "Modeling the Waveguide Invariant as a Distribution," *AIP Conference Proceedings*, **621**, 137-150, (2001).
6. D. Rouseff and L.M. Zurk, "Striation-based beamforming for estimating the waveguide invariant with passive sonar," *J. Acoust. Soc. Am.*, **130**(2), EL76-EL81, (2001).
7. A.W. Sell and R.L. Culver, "Waveguide invariant analysis for modeling time-frequency striations in a range-dependent environment," *J. Acoust. Soc. Am.*, **130**(5), EL316-EL322, (2011).
8. C. Tomasi and R. Manduchi, "Bilateral Filtering for Gray and Color Images," *Proceedings of the IEEE International Conference on Computer Vision*, (1998).
9. R.J. Urick, "Radiated noise of ships, submarines, and torpedoes: radiated-noise levels," in *Principles of Underwater Sound, 3rd Edition*, edited by D. Heiberg and J. Davis, McGraw-Hill, (1983).


## PUBLICATIONS

Sell, A. W. and R. L. Culver (**2011**). "Waveguide invariant analysis for modeling time-frequency striations in a range-dependent environment," J. Acoust. Soc. Am., vol. 130, no. 5, pp. EL316-322, November 2011.

Jemmott, C. W. and R. L. Culver (**2011**). "Single-Hydrophone Model-Gased Passive Sonar Source Depth Classification," IEEE J. Ocean. Eng., vol. 36, no. 4, pp. 696-702, October 2011.

Sell, A. W. and R. L. Culver (**2012**). "Using broadband, ship-radiated noise in shallow water environments to perform physics-based localization," presented at Inter-Noise 2012, August 19-22, 2012, NY, and available from the Institute of Noise Control Engineering (INCE/USA) http://scitation.aip.org/INCE/.

Bissinger, B. E. and R. L. Culver (**2012**). "Model-Based Signal Processing for Passive Sourcc Localization," Proceedings of the 11th European Conference on Underwater Acoustics, Edinburgh, Scotland, 2-6 July 2012.

**HONORS/AWARDS/PRIZES**

None.